Deployment of a Multi-Chip NFC System with Microfluidic for Electrochemical Sensing

Giulio M. Bianco(1), Vincenzo Mazzaracchio(2), Luca Fiore(2), Fabiana Arduini(2), Gaetano Marrocco(1), and Cecilia Occhiuzzi(2)

(1) Pervasive Electromagnetics Lab, University of Rome "Tor Vergata", Italy, http://www.pervasive.ing.uniroma2.it/
(2) Department of Chemical Science and Technologies, University of Rome "Tor Vergata", Italy, http://www.nanobiosensing.com/

***Abstract*— Fast, on-site chemical sensing can be a powerful tool for many applications, ranging from point-of-care analyses to food quality checks. NFC (Near Field Communications) devices capable of chemical sensing have recently become available. However, they are still limited to sensing a single chemical species at a time, whereas usually, an array of species should be quantified during the same analysis. Multi-chip NFC devices are still unavailable for chemical sensing, and the use of microfluidics with delay lines is also necessary for the correct delivery of liquid samples. Accordingly, this contribution explores the layout design of the first multi-chip NFC system integrated with microfluidics for electrochemical sensing using multiple boards simultaneously. The most functional arrangement of the responders is experimentally selected based on their read areas, the quality of the NFC communication, and the microfluidic characteristics. Lastly, a four-channel microfluidic system is integrated with the best board placement and validated by quantification of sodium in standard solution.**

I. INTRODUCTION

Electrochemical analysis systems play an increasingly crucial role in various applications, including Points-of-Care (PoCs) [1] and food sensing [2]. NFC devices for rapid on-site chemical analyses have recently been proposed and developed [3], [4], even in epidermal and flexible forms [5]. However, their limitation lies in quantifying only a single chemical species. Instead, more complex sensor arrays readable by smartphones would open avenues for diverse applications, such as oncology therapy [6]. Therefore, a multi-chip NFC system for electrochemical sensing integrated with microfluidics would constitute a technological advancement allowing for a plethora of applications. This contribution preliminarily investigates such a system by exploiting recently commercialized boards for open circuit potentiometry and manufacturing a first design of paper-based microfluidics, which comprises *i*) "input pad(s)" where the liquid is deposed, *ii*) "sensing pads" superimposed to each sensing electrode, and *iii*) "waste pads" to collect liquid after sensing is completed.

II. SYSTEM DEPLOYMENT BY EM EVALUATION

The system to be deployed, hence, must perform chemical analyses on four different chemical species in liquids such as blood, saliva, or fluids resulting from food spoiling. It must be battery-less, portable, and deliver the liquid to the sensing electrodes by using a microfluidic circuit at the exact time of the interrogation for maximum accuracy. Since they are single-use, easily replaceable electrodes and microfluidic must be employed, so that the microfluidic channel must be composed by a unique piece of paper. To ensure flowing of liquid, then, waste pads must be designed in a symmetric way w.r.t. the sensing pads. All the boards should be easy to read to maximize usability.

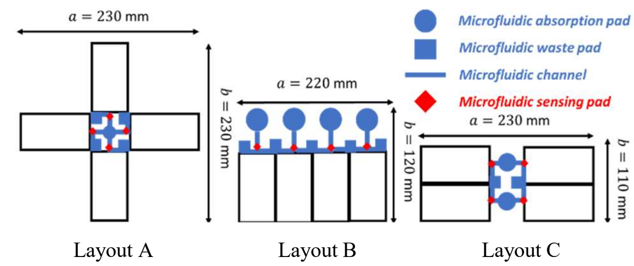

Figure 1. The three considered layouts of the NFC system: layout A, layout B, and layout C. The external size $\{a, b\}$ for each configuration is reported, as well as the starting geometry for the corresponding microfluidic circuit.

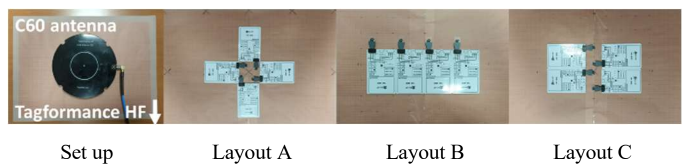

Figure 2. Experimental setup and tested NFC system's layouts.

As a first step, the system should maximize the following KPI (key performance indicators): 1) the more similar read areas of the four boards, 2) the larger read area, 3) the stronger responder-interrogator coupling possible, and 4) the lower number of input pads, i.e., different drops of liquid required for sensing (for the sake of the accuracy and easiness of the chemical analysis).

The novel integrated circuit SIC 4343 [7] (by SIC Technology) capable of open circuit potentiometry, was selected, and the commercial FlexSense (by SIC Technologies) board was used. Three layouts of the NFC system were conceived and are reported in Fig. 1. All the layouts use a unique microfluidic circuit for ease of replacement and if needed multiple input pads to shorten the channel, which can lose sampling liquid due to the material (viz., absorbing paper) yield. The performances of the three arrangements are quantified here by using a grid with graph paper and the HF functionality of Tagformance Pro (by Voyantic) while utilizing the C60 interrogation antenna (an antenna composed by 4 loops having a diameter of 60 mm).

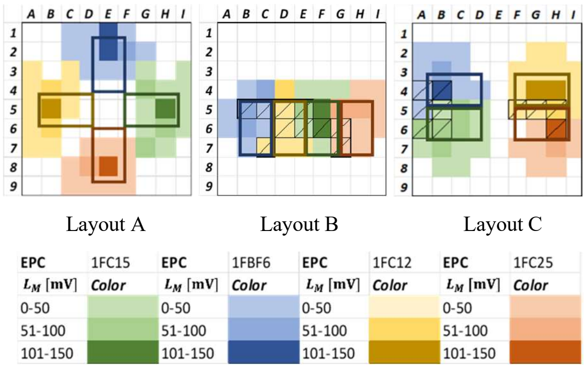

Figure 3. Coverage maps of the three system layouts and measured load modulation, reporting the boards' positioning. Bordered squares denote that two responders communicated in the same area. In no area more than two boards have ever responded.

The KPI can be mathematically evaluated by the following objective functions:

$$o_1 = \frac{1}{2}\left\{\frac{\sum_i A_i}{A_T} + \left[1 - \frac{\sum_{i \neq j}(|A_i - A_j|)}{C(M,2)A_T}\right]\right\} \quad (1)$$

$$o_2 = \frac{\sum_i\left[\iint_{A_T}\left(\int_P L_{M,i}\right)\right]}{4\iint_{A_T}\left(\int_P L_{M,0}\right)} \quad (2)$$

$$o_3 = \frac{M-N}{M} \cdot \frac{M}{M-1} \quad (3)$$

where: $\{o_1, o_2, o_3\}$ are three objective functions concerning read areas, communication, and number of required samples, respectively; A_i is the read area of the i-th responder; $A_T = 24$ cm $\times$ 24 cm is the overall test area; $M = 4$ is the number of NFCs chip in the system; $N \in [1; M]$ is the number of samples needed (see the circular pads in Fig. 1); $C(\cdot,\cdot)$ is the factorial function; L_M is the (passive) load modulation, and the pedixes *i* and *0* denote the *i*-th board and a single board in the absence of the others; the integration domain P refers to the whole set of powers for the interrogation sweep from 0.5 dBm to 24 dBm by power step of 0.5 dBm. All the objective functions have positive values ≤ 1 to equally contribute to the optimum definition, and the higher the o_i value, the better the system performance. The load modulation quantifies the strength of the responder's signal [5]. The three system layouts were tested, including sensing electrodes (Fig. 2). The load modulation measured by the Tagformance HF was then processed by using Matlab R2021b. If two boards responded in a sector, the sector was attributed to the stronger-responding board based on $\int_P L_{M,i}$, obtaining the coverage map in Fig. 3. The o_2 values reported in Table I show some coupling effects due to the proximity of coils in layout B. Layout A outperforms the other two, mainly thanks to the single input pad of its microfluidic circuit ($o_3 = 1$), allowing for easier use of the system. In the end, a test for sensing of Na (sodium) using ad-hoc screen-printed electrodes [8] and obtaining good agreement with a commercial potentiostat (PalmSense 4; Fig. 4), with some uncertainty which is due to *i*) electrodes manufacturing, *ii*) non-optimized microfluidic, and *iii*) different powers delivered through the NFC link. These issues can be addressed by optimizing the microfluidic circuit and fixing each interrogator-responder distance.

TABLE I. EVALUATED o_i AND OVERALL SCORE OF EACH LAYOUT

Layout	$\mathbf{o_1}$	$\mathbf{o_2}$	$\mathbf{o_3}$	$\sum_i \mathbf{o_i}/3$
A	0.87	0.96	1	0.94
B	0.72	0.86	0	0.53
C	0.82	1	0.67	0.83

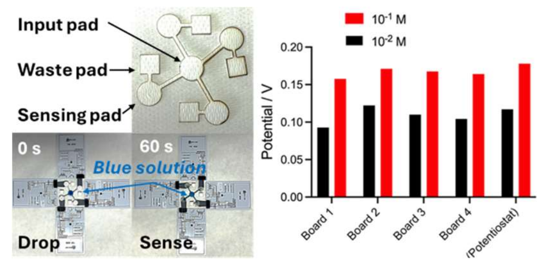

Figure 4. System integration and test for sodium sensing. A zoomed-in picture of the microfluidic and test with *Molybdenum blue* 1 mM are shown on the left.

III. Conclusion and Ongoing Work

In this contribution, we investigated the positioning of multiple NFC boards for electrochemical sensing from four sensing electrodes simultaneously, thanks to a microfluidic circuit. A coupling effect between the multiple coils was observed, even though it depends on the form factors of the interrogator's coil as well as on that of the responder's ones. We plan to test the system in clinical settings and optimize the microfluidics for blood sensing by investigating possible materials and the use of delays in the channels. Additional results will be presented at the conference.

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References

[1] G. M. Bianco *et al.*, "UHF RFID and NFC Point-of-Care—Architecture, Security, and Implementation," in *IEEE Journal of Radio Frequency Identification*, vol. 7, pp. 301-309, 2023.

[2] A. Hassoun *et al.*, "Implementation of relevant fourth industrial revolution innovations across the supply chain of fruits and vegetables: A short update on Traceability 4.0," in *Food Chemistry*, 2023.

[3] A. Lazaro, R. Villarino, M. Lazaro, N. Canellas, B. Prieto-Simon, and D. Girbau, "Recent Advances in Batteryless NFC Sensors for Chemical Sensing and Biosensing," in *Biosensors*, vol. 13, no. 8, pp. 1-40.

[4] K. Krorakai, S. Klangphukhiew, S. Kulchat, and R. Patramanon, "Smartphone-Based NFC Potentiostat for Wireless Electrochemical Sensing", in *Applied Sciences*, vol. 11, no. 1, pp. 1-13.

[5] A. B. Barba, G. M. Bianco, L. Fiore, F. Arduini, G. Marrocco and C. Occhiuzzi, "Design and Manufacture of Flexible Epidermal NFC Device for Electrochemical Sensing of Sweat," *FLEPS 2022,* 2022.

[6] S. Jiang, X. Chen, J. Lin, and P. Huang, "Lactate-Oxidase-Instructed Cancer Diagnosis and Therapy," in *Advanced Materials*, 2023.

[7] Silicon Craft Technology, "SIC Factsheet", 2023. https://documents.sic.co.th/popup/SICProductAll_20230426.pdf

[8] V. Mazzaracchio *et al.*, "All-solid state ion-selective carbon black-modified printed electrode for sodium detection in sweat," in *Electrochimica Acta*, Oct. 2021